Rummaging through Earth's attic for remains of ancient life

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ABSTRACT

We explore the likelihood that early remains of Earth, Mars, and Venus have been preserved on the Moon in high enough concentrations to motivate a search mission. During the Late Heavy Bombardment, the inner planets experienced frequent large impacts. Material ejected by these impacts near the escape velocity would have had the potential to land and be preserved on the surface of the Moon. Such ejecta could yield information on the geochemical and biological state of early Earth, Mars and Venus. In order to determine whether the Moon has preserved enough ejecta to justify a search mission, we calculate the amount of Terran material incident on the Moon over its history by considering the distribution of ejecta launched from the Earth by large impacts. In addition, we make analogous estimates for Mars and Venus. We find, for a well mixed regolith, that the median surface abundance of Terran material is roughly 7 ppm, corresponding to a mass of approximately 20,000 kg of Terran material over a 10 x 10 square km area. Over the same area, the amount of material transferred from Venus is 1-30 kg, and material from Mars as much as 180 kg. Given that the amount of Terran material is substantial, we estimate the fraction of this material surviving impact with intact geochemical and biological tracers.

Key Words: Surfaces, planets; Terrestrial planets; Earth; Moon

I. INTRODUCTION

The frequency of both lunar and Martian meteorites on the Earth indicates that the transfer of planetary material is common in the solar system. Vigorous hydrologic or tectonic cycles, past or present, prevent most nearby planetary bodies from serving as long-term repositories of this material. The Moon is an important exception, however. Strategically located within the inner solar system, the Moon has theoretically collected material from all of the terrestrial planets since its formation. Lacking an atmosphere and widespread, long-lasting volcanism, the Moon has potentially preserved meteorites from Mercury through the asteroid belt. While the lack of an atmosphere prevents a soft landing on the lunar surface, its low gravity means particles with small velocities with respect to the Moon will experience relatively low impact velocities. Moreover, unlike on other terrestrial planets, Martian, Venusian and Terran meteorites, blasted off their respective planets 3.9 Ga during the Late Heavy Bombardment, should still exist on the surface of the Moon. Such meteorites are likely to contain uniquely preserved remains of these planets that are not available elsewhere in the Solar System. In particular, Terran meteorites on the Moon may provide a substantive geological record for ancient Earth, corresponding to or predating the period for which the earliest evidence for life exists.

In considering the argument in favor of searching the Moon for Terran meteorites, the SNC meteorites represent obvious analogs. A considerable amount of Martian geoscience is built upon little more than a dozen samples. From them have been inferred important constituents of the atmosphere, mantle and core, the extent of interaction between the Martian hydrosphere and lithosphere, constraints on Martian water abundance, and the nature of a

Martian carbon sink, while the lightly shocked condition of the meteorites has stimulated developments in the understanding of impact physics (McSween 1994). Terran meteorites have the potential to provide similar information, extending and broadening Earth's geologic record for a time period that has otherwise left little or no physical evidence. The rocks' elemental composition and mineralogy (in particular, hydration) could be used to constrain characteristics of the early crust and mantle, the global oxidation state, the extent of planetary differentiation, and the availability of water. Volatile inclusions sampling noble gases, carbon dioxide and molecular nitrogen could clarify atmospheric origin and evolution and, along with the meteorite mineralogy, could provide substantive constraints on early atmospheric concentrations (Bogard and Johnson 1983). Direct measurement of the timing, extent and planetary effects of the heavy bombardment by careful dating of Terran meteorites is also possible and would perhaps be the most robust and significant scientific reward of this project.

In addition to the scientific benefits listed above, which alone justify searching the Moon for Terran meteorites, a fraction of Earth-derived material on the Moon could contain geochemical and biological information, in the form of isotopic signatures, organic carbon, molecular fossils, biominerals or even, theoretically, microbial fossils. Again, analogy to SNC meteorites is instructive. Questionable interpretations of structures within the Martian meteorite ALH84001 as microbial fossils (McKay *et al.* 1996) and, more recently, evidence supporting deposition there of magnetite by biomineralization (Thomas-Keprta *et al.* 2001; Friedmann *et al.* 2001) have been used to argue that this meteorite contains vestiges of ancient Martian life. While such interpretations remain highly controversial, they support the general principle that Terran meteorites should be examined for potentially novel evidence concerning early Earth life. Such evidence could substantiate or extend a contested fossil record that begins 3.5 Ga (Awramik 1982; Schopf and Packer 1987; Buick 1990; Brasier *et al.* 2002) and geochemical evidence from even earlier periods, between 3.7 and 3.85 Ga (Schidlowski 1988; Mojzsis *et al.* 1996; Rosing 1999; but see Moorbath 2001 and Fedo and Whitehouse 2002).

In addition, the Moon may preserve material not only from Earth, but also from Venus and the asteroid belt. The only attainable record of Venus' early surface geology, otherwise catastrophically erased 700 million years ago (McKinnon *et al.* 1997), is probably on the Moon. Similarly, a record of the type, characteristics and origins of the heavy bombardment impactors themselves may be available on the Moon. Such a record would clarify not only the geological history of Earth, but also its chemical and biological history – especially since these impactors were potentially major sources of biotic precursors on early Earth (Pierazzo and Chyba 1999).

Mars is presently the focus of attention with regard to the search for early signs of life outside Earth. Ironically, the Moon may be the better place to search for the remains of both early Martian and early Terran life. Most significantly, the Moon lacks the water capable of carrying contaminants into the interior of rocks through cracks. While gardening from micrometeorites is less severe on the surface of Mars, the deeply buried regolith on the Moon provides some protection. Finally, the Moon is also a perfect testbed for targeted sample return.

For these reasons, we determined the likelihood that early remains of Earth, Mars, and Venus have been preserved on the Moon in high enough concentrations to motivate a search mission. While others (Gladman 1997; Halliday *et al.* 1989) provide estimates for the transfer efficiency and total number of Martian meteorites impacting the Earth, there are no estimates for the abundance of Terran, Martian, and Venusian meteorites on the Moon. In Section 2, we consider the transfer of impact ejecta from Earth to the Moon's surface immediately following an impact event. By considering both the slow moving, Earth-bound ejecta and the high velocity ejecta that achieves orbit around the Sun, we estimate the total transfer efficiency of the material. Through a separate numerical simulation, we estimate a rough transfer efficiency for Venusian material. Additionally, we compute the range of expected impact velocities on the surface of the Moon. In Section 3 the results of Section 2 will be combined with mass flux estimates to calculate concentrations of Terran and Venusian meteorites on the Moon. In addition, the contribution from Martian meteorites is estimated from the literature. Section 4 includes a discussion of the survivability of the material delivered to the Moon via impacts over a range of velocities.

II. EJECTA TRANSFER FROM EARTH TO THE MOON

Large impacts on the Earth generate ejecta with launch velocities near to or exceeding the escape velocity. This material interacts with the Moon in a number of ways. Ejecta with speeds near the escape velocity eventually falls back to the Earth, gets swept up by the Moon, or achieves a stable orbit around the Earth. Ejecta with velocities exceeding the escape velocity either hits the Moon while escaping the Earth-Moon system, or achieves a stable solar orbit. We explore the velocity distribution of the ejecta from low speeds that just allow particles to reach the lunar orbit, up to speeds exceeding the escape velocity. We break the velocity distribution into three regimes:

1. Ejecta with launch speeds less than the escape velocity, but still large enough to reach the lunar orbit. The minimum velocity is determined by the Earth-Moon distance, as discussed below. This ejecta has a sufficiently low relative velocity with respect to the Moon that gravitational focusing is important. We refer to this as "direct transfer," and use geometrical and analytical methods to derive the amount of material that reaches the Moon via this process.

2. Ejecta that leaves the Earth-Moon system without interacting with the Moon and achieves a solar orbit, with the potential of interacting with the Earth and Moon at a later time. This includes all ejecta with velocities greater than the escape velocity. We refer to this regime as "orbital transfer," and use numerical simulations similar to Gladman 1997 to compute the transfer efficiencies.

3. Ejecta that leaves the Earth with speeds greater than the escape velocity and just happens to hit the Moon as it leaves the system. These high velocity "lucky shots" are estimated along with the numerical calculations.

A. Analytical treatment of direct transfer

The analysis for direct transfer treats the ejecta as a shell of material emanating from the surface of the Earth. This shell is defined by its leading and trailing edges, and the total volume increases with time as the shell rises ballistically from the Earth's surface. As this volume increases, the mean density of material within the shell is reduced. When the leading edge reaches the lunar orbit, the shell interacts with the Moon until the trailing edge also reaches the lunar orbit. Ideally, this entire process then repeats in reverse, ignoring the perturbing influence of the Moon, as the shell free-falls back to the surface.

It is important to realize the role of the lunar period in this transfer method. The transfer of material will be most efficient when the Moon is closest to the Earth, at 3.8 - 3.9 Ga. The density of material in the shell is determined by the lunar orbit, which was much smaller in earlier epochs. In addition, the amount of mass incident on the Earth during the Late Heavy Bombardment (and thus the mass of ejecta thrown up by these impacts) was much higher. These two effects have the potential to transfer large amounts of Terran ejecta, as described in Section 3.

The Moon's present mean distance from the Earth, in units of Earth radii, $R_\oplus$, is $\sim 60R_\oplus$, and it is receding at 3.82 $cm\ yr^{-1}$ (Dickey *et al.* 1994). Paleontology gives us constraints on this rate as far back as 2.5 Ga (Walker and Zahnle 1986). However, the rapid lunar recession in the first $\sim$ 700 Myrs prevents an accurate extrapolation to the late heavy bombardment epoch from present and paleontological data. A recent study (Zharkov 2000) attempts to estimate an early reference point for lunar recession. By assuming that the Moon's present shape was "frozen-in" during the Late Heavy Bombardment epoch, Zharkov uses the current data from the lunar gravity field and a model of its tidal interaction with the Earth to estimate this reference point. Zharkov estimates that the Moon's mean distance was $21.6R_\oplus$ about 3.9 Ga. We will adopt this value in our calculations, and as the starting point for discussions of the time evolution of the Moon's orbit subsequent to 3.9 Ga.

The leading edge of the shell is fixed by the escape velocity of the Earth (we consider material with velocities greater than the escape speed in Section 2.2). The trailing edge, however, is determined by the Earth-Moon distance. Thus, the maximum velocity is given by $v_{max} = 11.2\ km\ s^{-1}$ and the minimum velocity, v_{min}, is determined by considering conservation of energy in the Earth's potential:

$$v_{min} = v_{esc} \left(1 - \frac{1}{\eta}\right)^{\frac{1}{2}}, \tag{1}$$

where v_{esc} is the Earth's escape velocity and $\eta = \frac{R_{Moon}}{R_{\oplus}}$ is the distance between the Earth and the Moon divided by the Earth's radius. For the case of $\eta = 21.6$ at 3.9 Ga, $v_{min} = 10.94\ km\ s^{-1}$.

The position of the shell is determined by solving the system of equations governed by the Earth's gravitational potential,

$$\frac{\partial v}{\partial t} = -\frac{GM_{\oplus}}{r^2}; \qquad \frac{\partial r}{\partial t} = v, \tag{2}$$

where G is the gravitational constant, $M_{\oplus}$ is the Earth's mass, and r and v are the instantaneous position and velocity of the shell's edge. This set of equations is solved separately for the leading and trailing edges of the shell. From this, we can deduce the volume of the hemispherical shell,

$$V_{shell} = \frac{2}{3}\pi \left(r_{inner}^3 - r_{outer}^3\right), \tag{3}$$

where r_{inner} is the distance from the Earth to the trailing edge, and r_{outer} is the distance to the leading edge. The density of material within the shell, ρ_{shell}, is simply the mass ejected with speeds between v_{min} and v_{max} divided by this volume.

Chyba *et al.* 1994 calculate the amount of material leaving the surface with velocity greater than a given velocity, v, as

$$M_e\,(>v) = 0.11\,(\rho/\rho_t)^{0.2}\,(v_i/v)^{1.2}\,m, \tag{4}$$

where ρ and ρ_t are the density of the impactor and target, and v_i is the impact velocity. In the Earth's case the incident material is primarily from the asteroid belt and $v \sim 14\ km\ s^{-1}$ (Chyba *et al.* 1994; Bottke *et al.* 1994). Assuming $\rho = \rho_t = 2860\ kg\ m^{-3}$ for basalt, we derive that $M_e\,(>v_{min}) - M_e\,(>v_{max}) = 0.004\ m$ with $\eta = 21.6$ at 3.9 Ga. This amount will be reduced as the Moon recedes from the Earth over time.

The Moon will intersect the leading edge at a 45 degree angle, with a relative velocity, v_{rel}, determined by the quadrature sum of the leading edge velocity and the lunar orbital velocity. The incremental path length, dP, traversed by the Moon in a time dT is

$$dP = v_{rel} dT, \tag{5}$$

while the incremental mass swept up by the Moon is

$$dM = \rho_{shell} \sigma dP; \qquad \sigma = A_m \left(1 + \left(\frac{v_{esc,m}}{v}\right)^2\right), \tag{6}$$

where A_m is the cross sectional area of the Moon, and $v_{esc,m}$ is the lunar escape velocity. The gravitationally enhanced cross section, σ, is then integrated over the normalized velocity distribution, and the incremental mass, dM, is integrated from the time the leading edge reaches the Moon to the time the trailing edge reaches it. We multiply this total mass by a factor of 2 to take into account the reverse process of the shell falling back to the Earth. Table 1 shows the results of the model for nine positions of the Earth and Moon from 3.9 Ga to the present, corresponding to an Earth-Moon distance from 21.6 to 60.3 $R_\oplus$. In particular, we report F_{direct}, the fraction of mass reaching the Moon, as a function of the Earth-Moon distance in terms of the impactor mass.

[**Table 1**]

B. Numerical simulations of orbital transfer

A second method to transfer material from the Earth to the Moon is orbital transfer, which is much less sensitive to the Earth-Moon distance. Material leaving the Earth with a velocity greater than the escape velocity will remain in an Earth-like orbit as it travels around the Sun (i.e. roughly circular with a semi-major axis of about 1 Astronomical Unit (AU)). Over time, this material will interact with the Earth-Moon system. The goal of the numerical simulations is to determine the likelihood of impact with the Moon and Earth during a relatively short period of time.

The dynamical studies in this paper describe the ejecta as a spherically symmetric distribution traveling radially away from the planet, similar to the assumption adopted by Gladman 1997. In order to account for a range of velocities, we simulate the particles with velocities, v_∞, from 0.0 to 3.3 $km\ s^{-1}$, which is related to the launch speed, v_l, by

$$v_l^2 = v_{esc}^2 + v_\infty^2. \tag{7}$$

Since the Earth's escape velocity is large, this corresponds to a relatively narrow range of velocities, from 11.2 $km\ s^{-1}$ to roughly 11.7 $km\ s^{-1}$.

Each simulation consists of 225 ejecta particles, plus the nine planets and the Moon. The simulations were integrated using the dynamical integration code *pkdgrav* (Stadel 2001), employing a variable timestep to resolve close interactions with planets and resolve any collisions. Since the simulation includes a large range of orbital timescales the maximum timestep is determined by the object with the shortest orbital period which in our case is the Moon. To insure detailed calculation of the particle orbits, the number of integrations is maximized to a time resolution of 200 time steps per orbit. Given that the Moon is included and has the shortest dynamical time (orbiting the Earth once every 5.9 days at a distance of 21.6 $R_{\oplus}$), the maximum timestep is limited to 42 minutes. The minimum timestep is 1.5 minutes, sufficient to resolve any close encounters and collisions. The initial positions, velocities, and masses of the nine planets were taken from the DE 403 ephemeris, provided by the Jet Propulsion Laboratory. All of the simulations were run for 4775 years, each representing about 1 week of computing time on a modern desktop machine. The simulation results are recorded at approximately 5 year intervals for the entire integration.

During potential particle-planet encounters, the timestep is reduced to allow an accurate calculation of the interaction. The code uses a 16 rung multistepping ladder to reduce the time step from the maximum to the minimum required to resolve the encounter. Collisions are resolved at a timestep, n, by linearly extrapolating to possible encounters at the next timestep, $n + 1$, using velocities and positions of the particles at timestep n. Therefore, collisions with a small particle and a planet are well resolved, given a small enough timestep. However, errors in impact velocities can be significant. The velocity error is equal to $\delta T\ a$, where δT is the timestep, and a is the acceleration. At 1 AU from the Sun, in the absence of other potentials, this velocity error is only 1.5 $m\ s^{-1}$. However, at the Earth's surface, it can be as great at 800 $m\ s^{-1}$. To test the robustness of the code, we computed one simulation with half the timestep to make sure we recorded the same number of collisions.

For the purposes of this study, we are interested in orbital transfer of material over a relatively short period of time, less than 5000 years. We chose this interval to bias our results toward material that would be rapidly buried on the lunar surface, thus protecting it from degradation by UV radiation, cosmic rays, and micrometeorite weathering. However, since the material will continue to be transferred even beyond 5000 years, our results must be considered a lower limit on the total amount of Terran material delivered to the Moon by this process.

[**Figure 1**]

Looking more closely at the re-accretion of material onto the Earth, Fig. 1 shows the fate of 138 impacts in the $v_\infty = 0.0\ km\ s^{-1}$ case, depicting the cumulative number of impacts as a function of time. We see that 89% of re-accretion collisions occur within the first 100 years of the simulation, and 95% of the collisions have occurred within 1000 years. The remaining 5% of the reaccretion occurs between 1000 and 5000 years. We see from Table 2 that the quantity of ejecta returning to the Earth is greatest for $v_\infty = 0.0\ km\ s^{-1}$ and rapidly decreases for increasing v_∞. Over such a short period of time, and with simulations containing such small numbers of particles, lunar interactions with the ejecta are rare. We therefore estimate the amount of material interacting with the Moon from simple scaling arguments. We expect the ratio of the number of Earth impacts, $N_\oplus$, to the number of lunar impacts, N_{Moon} to be

$$\frac{N_\oplus}{N_{Moon}} = \frac{R_\oplus^2}{R_{Moon}^2} \frac{v_\infty^2 + v_{esc,\oplus}^2}{v_\infty^2 + v_{esc,m}^2 + v_{pot}^2}, \tag{8}$$

where $v_{esc,\oplus}$ and $v_{esc,m}$ are the escape velocities of the Earth and Moon, and $v_{pot} = \frac{v_{esc,\oplus}}{\sqrt{\eta}}$

represents the contribution of the Moon's proximity to the Earth's potential well. For the distance to the Moon chosen for our study, 21.6 $R_{\oplus}$, v_{pot} is approximately equal to the Moon's escape velocity, and gives a derived ratio of 140 for $v_{\infty} = 0.0\ km\ s^{-1}$. This matches well with the simulation for $v_{\infty} = 0.0\ km\ s^{-1}$, and allows us to scale the other results accordingly. Table 2 indicates these scaled results, along with derived lunar impact fractions and transfer efficiencies, F_e. We use Eq. 4 to determine the amount of material launched within a given velocity range, and use these values to derive the fraction of impactor mass transferred to the Moon, F_{orb}. These will be used in the following section to derive the mass flux from Earth to the Moon.

[**Table 2**]

C. Lucky shots

Finally, we take into account the "lucky shots" that impact the Moon on their way out of the Earth-Moon system. To first order, for fast moving particles, the fraction hitting the Moon is just the cross sectional area of the Moon divided by the surface area of an imaginary sphere encompassing the lunar orbit:

$$F_{lucky} = \frac{R_{Moon}^2}{4D_{Moon}^2}. \tag{9}$$

For the same conditions as the numerical simulation, namely $D_{Moon} = 21.6\ R_{\oplus}$, $F_{lucky} = 4.0 \times 10^{-5}$, the same as the transfer efficiency for the $v_{\infty} = 3.3\ km\ s^{-1}$ case. Given this similarity, when these high velocity "lucky shots" are included in the mass flux calculation, they are treated with the high velocity particles from the numerical simulations.

D. Lunar impact velocities

The sections above determine the fraction of ejecta reaching the Moon. However, the velocity distribution of this material must be calculated to determine the likely impact velocities on the Moon expected during lunar encounters. Since lightly shocked millimeter-sized chondritic meteorites are found in the lunar soil (McSween 1976; Melosh 1989), there is some hope of intact sample survival of even fast moving impactors.

To explore the impact velocities, we first address the velocity distribution of the ejecta launched from the surface of the Earth. Eq. 4, above, from Chyba *et al.* 1994 gives the integrated probability distribution in terms of the impactor mass. We start by taking the derivative of this equation to get the velocity distribution function for velocities within a range from v to $v + \delta v$,

$$P_v = C\frac{\partial M\left(> v\right)}{\partial v}, \tag{10}$$

where C is the normalization constant given by

$$C = \frac{1}{\int_{v_{min}}^{v_{max}} \frac{\partial M(>v)}{\partial v} dv}. \tag{11}$$

We take v_{min} and v_{max} from the full range of launch velocities, from 10.94 to 11.7 $km\ s^{-1}$. Thus, the probability of finding a launch velocity within the range of v and $v + \delta v$ is $\int_v^{v+\delta v} P_v dv$. Through conservation of energy in the Earth's potential and knowledge of the Moon's orbital velocity, v_{orb}, we can translate this into the interaction velocity at the Moon. Added to this is the Moon's escape velocity, $v_{esc,m}$, to get the maximum impact velocity for a given launch velocity

$$v_{i,max} = \left(v_{int}^2 + v_{orb}^2 + v_{esc,m}^2\right)^{\frac{1}{2}}, \tag{12}$$

where v_{int} is determined by

$$v_{int} = \left(v_l^2 + v_{esc,\oplus}^2 \left(1 - \frac{1}{\eta}\right)\right)^{\frac{1}{2}}. \tag{13}$$

The maximum impact velocity tells us about the total kinetic energy carried by the particle as it impacts the Moon's surface. This corresponds to a velocity of around 5 $km\ s^{-1}$ with $\eta = 21.6$. However, the impactor will disperse some of this energy during oblique impacts, and therefore the maximum impact velocity doesn't necessarily determine the amount of shock delivered to the impactor. Accordingly, we compute the vertical component of the velocity as the upper bound on the stress induced in the impactor. Measuring the impact angle, θ, from the ground (i.e. 90 degrees is a direct impact) the vertical component is given by

$$v_{vert} = v_{i,max} sin\theta. \tag{14}$$

The probability of a given particle having an impact angle between θ and $\theta + \delta\theta$ is given by $\int_{\theta}^{\theta+\delta\theta} P_\theta d\theta$. Pierazzo and Melosh 2000a show that this normalized distribution is

$$P_\theta = 2 sin\theta cos\theta \tag{15}$$

regardless of the planet's gravity field. Using this information, along with our velocity distribution, we compute the expected value of the vertical impact velocity, v_{exp}, over our range of velocities and for impact angles less than or equal to θ

$$v_{exp}\left(\theta\right) = \int_{v_{min}}^{v_{max}} \int_{0}^{\theta} P_{\theta} P_{v} v_{vert} d\theta dv. \tag{16}$$

Table 3 gives v_{exp} for a range of impact angles, and the corresponding probabilities for such angles, determined from Eq. 15.

[**Table 3**]

We can use the results from the orbital simulations to spot check the lunar impact calculations. We have one impact each for the $v_{\infty} = 0.0\ km\ s^{-1}$ and $v_{\infty} = 1.8\ km\ s^{-1}$: one at 3.9 $km\ s^{-1}$ and one at 4.2 $km\ s^{-1}$ occurring 140 years and 541 minutes after launch, respectively (This last impact represents one of the "lucky shots" impacting the Moon as it leaves the system.) These impact velocities correspond to the respective $v_{i,max}$ for each case. Both of the impacts occurred at roughly 30 degree impact angles, corresponding to a vertical velocity of 2.0 $km\ s^{-1}$ and 2.1 $km\ s^{-1}$, well within our most probable calculated vertical impact velocity.

The impact velocities also give us a rough estimate of the likelihood that an aggregate chunk of material will survive the impact in any recognizable form. Given the nature of our calculations, we want to derive the impact pressure experienced by the rock fragment upon impact. To get an order of magnitude estimate, we use simple scaling and dimensional analysis to estimate this quantity.

The total deceleration experienced by the rock fragment upon impact is approximately

$$a = \frac{v_{vert}}{\Delta T}, \tag{17}$$

where v_{vert} is the vertical velocity and $\Delta T = \frac{d}{v_{vert}}$ is the time it takes to traverse the diameter,

d, of the particle. We can estimate the mean impact pressure experienced by a particle by multiplying this deceleration by the mass of the particle and dividing by the cross sectional area of the particle. Thus, we derive an order of magnitude estimate for the mean impact pressure which is independent of the size of the impactor,

$$P_{ave} = \frac{2}{3}\rho v_{vert}^2, \tag{18}$$

with $\rho = 2860\ kg\ m^{-3}$ for basalt. Table 3 shows the results for a range of likely impactor velocities. These values are in rough agreement with the literature-based constraints we impose for ejecta leaving the surface of the Earth as described in Section 4. It should also be noted that dissipative effects of the regolith and other factors may reduce the impact pressure. Thus, for the range of impact velocities calculated in this section, the likelihood of Terran ejecta surviving in some large aggregate sample are quite high, as will be discussed in detail later.

III. MASS TRANSFER RATES

A. Mass transfer from the Earth to the Moon

Armed with transfer efficiencies from our analytical calculations and numerical simulations, we can compute the mass flux of Terran ejecta incident on the Moon. We will proceed in four steps:

1. Calculate the mass of material incident on the Earth during the period of interest, from 3.9 Ga to the present, scaled from the lunar impact record.

2. Determine the fraction of material that leaves the Earth with a given velocity during an impact event.

3. Apply the transfer efficiencies determined in the previous section to estimate the mass of material that reaches the Moon. Ejecta with velocities between 10.9 $km\ s^{-1}$ and 11.2 $km\ s^{-1}$ correspond to direct transfer efficiencies. Ejecta with larger velocities correspond to either the orbital transfer or lucky shot efficiencies.

4. Determine the fractional volume of this material in the lunar regolith by considering the other material accreted by the Moon at the same time, namely micrometeorite flux and ejecta from subsequent lunar impacts.

To gain an estimate of the mass flux incident on the Earth as a function of time, we follow the method described in Chyba *et al.* 1994, making use of the lunar cratering record. The cumulative crater density for craters greater than a given size, D, due to impactors incident on the Moon as a function of time can be modeled by an equation of the form

$$N\left(t, > D\right) = f\left(t\right) \times \left(\frac{D}{4\ km}\right)^{-1.8} km^{-2}\ Gyr^{-1}. \tag{19}$$

We consider two possible variations in the time dependence of this model. First, we explore the model employed by Chyba *et al.* 1994 which describes the impact history as being roughly constant for the past 3.5 Ga, and increasing exponentially for earlier times,

$$f_{exp}\left(t\right) = \alpha\left(t + \beta e^{t/\tau}\right). \tag{20}$$

We also consider the case of the lunar cataclysm, which includes a period of increased impact flux about 3.9 Ga. This is modeled by adding a Gaussian term,

$$f_{cat}(t) = f_{exp}(t) + \gamma e^{\frac{-(t-\mu)}{2\tau_c^2}}. \tag{21}$$

with $\mu = 3.9$ Ga, the peak of the cataclysm, and τ_c is the gaussian width of the event. Each of these equations are fit to the lunar data provided in the BVSP 1981. Since the lunar data are cumulative in both crater size and time, the data must be fit by the cumulative number density distribution

$$N_c(4\ km) = \int_0^{t_{age}} N(t, 4\ km)\ dt\ km^{-2}, \tag{22}$$

with $D = 4\ km$ as shown in Fig. 2. Similar to Chyba *et al.*, we perform a χ^2 minimization with the coefficients as free parameters, leaving the decay time, τ, and the width of the cataclysm, τ_c, fixed for each case (as noted in the table, τ for the case of the lunar cataclysm was modified slightly from Chyba's model to improve the fit). Table 4 details the parameter values and fit results graphically depicted in Fig. 2. The values for α and β given in Table 4 for the exponential case differ from those determined by Chyba *et al.* 1994, but the differences are not significant and can be traced to differences in the interpretation of data from BVSP.

[**Table 4**]

[**Figure 2**]

Following arguments similar to Chyba *et al.* 1994, we now calculate the mass incident on the Moon as a function of time. The mass of an impactor can be related to the final crater diameter,

$$m\left(D\right)=0.54\Gamma v^{-1.67}D_c^{0.44}D^{3.36} \tag{23}$$

where $\Gamma = 1.6{\times}10^3$ (with units of $kg\ s^{-1.67}$) is a constant for lunar values of the surface gravity and surface density (Chyba *et al.* 1994), v is the impactor velocity in $m\ s^{-1}$, $D_c = 11,000$ is the transition from craters with simple bowl shapes to more complex morphologies, and D is the final crater diameter, both in meters. Combining Eq. 23 with Eq. 19 gives a cumulative crater density for objects greater than a given mass, m,

$$n\left(t,>m\right)=f\left(t\right)\times\left(\frac{m}{m\left(4\ km\right)}\right)^{-b}km^{-2}\ Gyr^{-1}. \tag{24}$$

where $b = (1.8/3.36) = 0.54$. Furthermore, we can determine the total mass of impactors incident on the lunar surface per unit area as a function of time by integrating over the mass distribution

$$M\left(t\right)=\int_{m_{max}}^{m_{min}}m\frac{\partial n}{\partial m}dm. \tag{25}$$

Upon integration and the assumption that $m_{max} \gg m_{min}$, the total mass of objects incident on the surface per km^2 per Gyr is given by

$$M\left(t\right)=f\left(t\right)m(4\ km)^b\frac{b}{1-b}m\left(D_f\right)^{1-b}, \tag{26}$$

where $m\left(D_f\right)$ is the maximum mass impactor represented by the largest impact basin, taken by Chyba to be the $D_f = 2200\ km$ South Pole-Aitken crater.

In scaling these impactor fluxes to the Earth, we take into account the increased gravitational focusing of the Earth through the ratio of impact cross sections,

$$\frac{\sigma_{\oplus}}{\sigma_{Moon}} = \frac{R_{\oplus}^2}{{R_{Moon}}^2} \frac{1 + \left(\frac{v_{esc,\oplus}}{v_i}\right)^2}{1 + \left(\frac{v_{esc,m}}{v_i}\right)^2}, \tag{27}$$

where $R_{\oplus}$ and R_{Moon} are the radii of the Earth and Moon, $v_{esc,\oplus}$ and $v_{esc,m}$ are the escape velocities of the Earth and Moon, and v_i is the typical velocity of the interacting particle. If the particles are asteroids, with typical impact speeds of 14 $km\ s^{-1}$ (Chyba *et al.* 1994; Bottke *et al.* 1994), this ratio is ~ 24. Multiplying $M(t)$ by the area of the Moon and taking into account the ratio of impact cross sections gives the total mass of material incident on the Earth as a function of time.

Finally, we consider the transfer of material from the Earth to the Moon. In Section 2, we computed the total fraction of material transfered directly from the Earth to the Moon, $F_{direct}(t)$, as a function of time. The mass transferred via this method is

$$M_{dir}(t) = F_{direct}(t)\, M(t) \tag{28}$$

For orbital transfer, we determined the fraction of the impactor transferred from the Earth to the Moon, F_{orb}, at a distance of 21.6 $R_{\oplus}$. The mass of material ejected from the Earth at speeds greater than the escape velocity during these impacts is proportional to the mass of the incident material, m, determined from Eq. 4. Using $\rho = \rho_t = 2860\ kg\ m^{-3}$, we derive that $M_e(> v_{esc}) = 0.14\ m$.

Since the Earth does the bulk of the gravitational focusing when interacting with Sun-orbiting particles, as the Moon recedes from the Earth, the transfer efficiency will decrease in proportion to the ratio of gravitational potential of the Earth at a distance $R_0 = 21.6 R_{\oplus}$ and the instantaneous value, $D(t)$,

$$F_{orb}\left(t\right) = F_{orb}\frac{R_0}{D\left(t\right)}. \tag{29}$$

We take the instantaneous value of $D\left(t\right)$ to have the functional form described by Williams 2000,

$$D\left(t\right) = R_0\left[1 - \frac{13}{2}\frac{\langle\dot{R}\rangle}{R_0}\left(T_{ref} - t\right)\right]^{2/13}, \tag{30}$$

where $\langle\dot{R}\rangle = -673\ R_\oplus\ Gyr^{-1}$ is the average lunar recession velocity, and $T_{ref} = 3.9$ Gyrs is the reference time for our simulations when the Moon was 21.6 $R_\oplus$ from the Earth. $\langle\dot{R}\rangle$ is determined by taking $D\left(0\right) = 60.3\ R_\oplus$, the current lunar distance.

To determine the total mass transferred to the Moon, we multiply the ejected material by the transfer fraction

$$M_{orb}\left(t\right) = F_{orb}\left(t\right)M\left(t\right). \tag{31}$$

Table 2 shows the fraction of material launched for a given v_∞. The "lucky shots" are included in the last integral, since the transfer efficiencies are the same as for $v_\infty = 3.3\ km\ s^{-1}$. The relative contributions from orbital and direct transfer show that orbital transfer dominates for the last 3.9 Ga. At 3.9 Ga, orbital transfer accounts for 58% of the total transferred mass. The orbital contribution almost completely dominates at the present epoch.

It should be noted that these transfer methods ignore the inhibiting effects produced by the Earth's oceans and the Earth's atmosphere. However, we are considering only large impactors, and our condition that $m_{max} \gg m_{min}$ must be satisfied. To put this in perspective, the mass of the impactor that formed the South Pole-Aitken Crater is roughly $1.5 \times 10^{19}\ kg$.

If we only consider impactors larger than 10 km (roughly the scale height of the Earth's atmosphere, and also larger than the depth of the Earth's ocean), this corresponds to a mass of 1.5×10^{15} kg, a factor of 10^{-4} less than m_{max}. In addition, impacts of this size should excavate enough atmosphere for ejected material to leave the Earth with minimal interaction (Melosh 1988).

B. Burial on the lunar surface

As the Terran material reaches the Moon, it will be buried by the accretion of micrometeorites and ejecta from subsequent lunar impacts. Love and Brownlee 1993 measured directly the flux of micrometeorites incident on the Earth today to be $M_{micro} = 4 \times 10^{16}$ kg Gyr^{-1}. In the absence of other constraining evidence, we take this to follow the time dependence of Chyba *et al.* 1994, and scale it to the Moon by considering the difference in surface area and gravitational focusing between the Earth and Moon.

The mass of ejecta, crudely averaged over the surface of the Moon, can be determined from methods described in Sleep and Zahnle 2001. We scale the mass of ejecta produced in a given impact to the volume of material removed from the crater. Cast in terms of the Moon's escape velocity and the mass of the impactor, the relationship is

$$m_{ej}(m) = 18.2 \left(R_{Moon}\right)^{0.65} \left(\rho_t\right)^{0.217} \left(\frac{v_i}{v_{esc,m}}\right)^{1.3} m^{0.783}, \qquad (32)$$

where v_i is the impact velocity on the Moon, R_{Moon} is the radius of the Moon in meters, and ρ_t is the density of the lunar surface, taken to be 2860 kg m^{-3}, and m is the impactor mass, in kilograms. To determine the total amount of ejecta produced on the Moon as a function of time, we integrate this over the impactor distribution, Eq. 25,

$$M_{ej}\left(t\right) = \int_{m_{max}}^{m_{min}} m_{ej}\left(t\right) \frac{\partial n}{\partial m} dm. \tag{33}$$

Again, assuming $m_{max} \gg m_{min}$ and $b = 0.54$, the total mass of ejecta as a function of time is

$$M_{ej}\left(t\right) = 40.4 \left(R_{Moon}\right)^{0.65} \left(\rho_t\right)^{0.217} \left(\frac{v_{esc,m}}{v_i}\right)^{1.3} m \left(4\ km\right)^b f\left(t\right) m \left(D_f\right)^{0.243}. \tag{34}$$

Thus, the total amount of ejecta available to bury Terran material is this amount minus the amount lost to space, determined by Eq. (4), with appropriate lunar parameters.

At this point, for each of the contributions of Terran sources, micrometeorites, and subsequent lunar ejecta (collectively denoted M_{cont}, below), we define an equivalent thickness of material per square kilometer per Gyr (averaged over the surface of the Moon)

$$H\left(t\right) \equiv \frac{M_{cont}\left(t\right)}{\rho}, \tag{35}$$

with the densities, ρ, of the various materials taken to be 2860 $kg\ m^{-3}$ for the ejecta and Terran material, and 2200 $kg\ m^{-3}$ for the micrometeorites. The fractional volume of Terran material accreted subsequent to a time, t_{age}, is determined by integrating each of the contributions up to the age of the surface in question and taking the ratio of the volume of Terran material to the other sources

$$\frac{V_{ter}}{V_{other}} = \frac{\int_0^{t_{age}} H_{ter} dt}{\int_0^{t_{age}} H_{micro} + \int_0^{t_{age}} H_{ej} dt}. \tag{36}$$

Finally, the total depth of material accreted since a time t_{age} is determined by summing the contributions of all three materials,

$$H_{total} = \int_0^{t_{age}} H_{micro} + H_{ej} + H_{ter}\ dt. \tag{37}$$

Fig. 3 shows H_{total} as a function of time, with most of the material contributing to the depth of lunar regolith deposited during and shortly after the Late Heavy Bombardment, from 3.9 to 3.8 Ga. Fig. 4 shows the fractional volume, or mixing ratio, of Terran material as a function of time. Again, the highest fraction occurs from 3.8 to 3.9 Ga, when the Moon's proximity to the Earth facilitated transfer.

[**Figure 3, Figure 4**]

These calculations, however, are a lower limit on the amount of Terran material accreted by the Moon. Sleep *et al.* 1989, and subsequently Chyba *et al.* 1994, point out that, due to small number statistics, the Moon under-samples the largest impactors. Chyba *et al.* 1994 predict more impacts on the Earth, and argue that an impactor of mass $\sim 1.4 \times 10^{22}\ kg$ was probable subsequent to 4.4 Ga. Using Eq. 4 and a simple average of our transfer efficiencies, 1.5×10^{-6} times the mass of the impactor, as much as $6 \times 10^{8}\ kg\ km^{-2}$ of material will reach the Moon, corresponding to an equivalent basalt thickness of 0.2 km. However, it is impossible to tell when this material may have arrived on the Moon, depending as it does on a very few large impacts occurring stochastically through time. In addition, these impactors were likely accreted long before the end of the Late Heavy Bombardment, and thus before the formation of the lunar maria. Therefore, we ignore this contribution in the above calculation, but note that this very significant amount will most likely be buried and possibly protected by the formation of the maria. However, if subsequent impacts break through the maria, this reservoir of Earth material may be exposed to the surface. According to our calculations, it would be necessary to excavate to a depth of at least 300 meters (and most likely more) to gain access to this layer of Terran material. Assuming a crater diameter to excavation depth ratio of 10 to 1 (Melosh, 1989), any crater 3 km in size or greater should provide a window to this layer.

Finally, the effects of gardening (the breakup and mixing of the lunar regolith by micrometeorites and larger impactors) on the vertical distribution of this material will be substantial. Lunar cores from the Apollo missions directly indicate vertical mixing of up to one meter (Mustard 1997), and samples indicating deep mixing to tens of kilometers have been found (Lindstrom and Lindstrom 1986). While most of the very deep mixing occured before the period of interest, we can expect that the regolith will be well mixed to the depths indicated in this study. Therefore, any sampling of the lunar stratigraphy will have a coarse time resolution at best. This mixing may facilitate easier retrieval of samples over a range of potential ages, as subsequent small impacts will excavate older material directly to the surface. The amount of Terran material on the surface of the Moon will depend largely on the age of the surface that is searched. Assuming the regolith is well mixed, we estimate the total surface abundance of Terran to lunar material to be 7 ppm. This corresponds to $\sim 20,000\ kg$ of Terran material over a 10 x 10 square km area..

C. Mass transfer from Venus and Mars to the Moon

We also explored the fate of material transferred from Venus and Mars to the Moon. Due to Venus' proximity to the Sun, the velocity required to launch a particle from the surface with enough energy to reach an Earth crossing orbit is $v_\infty = 3.3\ km\ s^{-1}$. We performed one simulation for Venus, tracking 225 particles for about 5000 years. After this period of time, only one particle hit the Earth. Thus, subject to the errors of small number statistics, the Venus-Earth transfer efficiency is $\sim 4 \times 10^{-3}$. Using our scaling for the gravitational cross sections of the Earth and Moon further reduces this transfer efficiency, on average, by another factor of $\sim 10^{-5}$, giving a Venus-Moon transfer efficiency of 1.2×10^{-7}. This is 30,000 times less than the Earth-Moon transfer efficiency of 4×10^{-3} for particles leaving the Earth with the escape speed, indicating that Venus rocks on the Moon will be a rare find indeed. Still, an area of 10 x 10 square km should still yield almost 1 kg of Venusian material, if it can be identified as such. Moreover, our estimate is a strict lower limit. Melosh and Tonks 1993, in a simulation of the fate of ejecta from other planets, indicates that about 30% of the ejecta leaving Venus with a wide range of velocities from $v_\infty = 0.0$ to $5\ km\ s^{-1}$ hits the Earth within 12 million years. This results in a Venus-Moon transfer efficiency of $\sim 3 \times 10^{-6}$, only about 1000 times less than the Earth-Moon transfer efficiency for particles launched from Earth with the escape speed. This means up to 30 kg of Venusian material could exist in the same 10 x 10 square km area.

The situation for Mars rocks is more optimistic. Estimates from Gladman 1997 and Halliday *et al.* 1989 indicate that fifteen 100-gram Mars rocks impact the Earth each year. Scaling this to the Moon, and assuming the amount of Martian material scales with the same time dependence as the rest of the incoming debris, we expect 6×10^{-8} of the lunar material to be Martian in origin, corresponding to about 180 kg in the same 10 x 10 square km area.

IV. SURVIVABILITY OF BIOLOGICAL AND GEOCHEMICAL TRACERS

Having calculated the mass fraction of Terran material on the Moon, we can now estimate the forms of evidence such material may contain. First, we identify physical constraints for specific evidence types. Then, we determine the planetary ejection and lunar impact regimes in which those constraints are satisfied. Finally, we convert this into a mass fraction of Terran material on the Moon corresponding to the given evidence type for different impactor velocities.

A. Constraints on survival of biological and geochemical evidence

The pressures and temperatures experienced by the Terran material during ejection from Earth and deposition on the Moon will determine the survival of biological and geochemical evidence. Although the impact temperatures, pressures and fates of targets have been extensively considered, little information is available about these conditions in the projectile during and subsequent to impact (Pierazzo and Melosh 2000b). Given this scarcity, and to avoid the complications of various equations of state and impact parameters, we establish general and approximate criteria to estimate the survivability of four different types of evidence: isotopes, significant volatile inventories, organic carbon, and molecular fossils (biomarkers). We emphasize that these calculations are intended only as an order of magnitude approximation for the amount of material experiencing conditions conducive to the possible survival of these evidence types.

1. Isotopes

Carbon isotope systematics have been interpreted as evidence for life on Earth as early as 3.85 Ga (Mojzsis *et al.* 1996). Similarly, other isotopes could also serve as biosignatures, for example, nitrogen or oxygen (Blake *et al.* 2001). Analysis of biological isotope fractionations requires comparison of a putative biological fractionation to the background signature of the host rock. Effectively, this imposes the condition that the Terran material avoid significant melting. Following Melosh 1988 and Stoffler *et al.* 1991, we set the onset of melting at a pressure of 70 GPa, recognizing that this value actually varies according to specific mineral assemblages and porosities. We assume that most material in a 5 $km\ s^{-1}$ impact on the Moon will not attain peak pressures greater than this and thus should avoid substantial melting, as indicated by Ahrens and O'Keefe 1971, Kipp and Grady 1996, and our own calculations (Table 3). Since all lunar impacts due to direct and orbital transfer occur at velocities $<$ 5 $km\ s^{-1}$, the fraction of material remaining solid is determined by the material ejected from Earth at pressures less than 70 GPa.

2. Significant volatile inventories

Tyburczy *et al.* 1986 empirically determined the percent volatile loss of a carbonaceous chondrite as a function of the projectile velocity. At velocities slightly greater than 2.0 $km\ s^{-1}$ and peak shock pressures $<$ 30 GPa, 50 % of projectile volatiles were lost. We therefore limit ejection to 30 GPa and lunar impact velocities ≤ 2.0 $km\ s^{-1}$.

3. Organic carbon

Empirical (Tingle *et al.* 1992; Tingle 1998; Tyburczy *et al.* 1986) and theoretical (Pierazzo and Chyba 1999) work suggests significant organic carbon fractions can survive impacts. In the experiments of Tingle *et al.* 1992, only small amounts of organic carbon were lost for impacts up to 2 $km\ s^{-1}$ and pressures up to 10 GPa. Although other work has suggested more significant losses (e.g. Peterson *et al.* 1997), we adopt as our constraints a maximum pressure during ejection of 10 GPa and lunar impact velocities $\leq 2.0\ km\ s^{-1}$. We also note that the very fact that organic carbon can survive some impact conditions implies the need for rigorous criteria to distinguish extraterrestrial and terrestrial organic carbon.

4. Molecular Fossils

To our knowledge, no information is available concerning survival of molecular fossils under impact conditions. In fact, impact conditions are likely to far exceed the nonetheless severe exigencies (temperatures $\sim$ 300 C, pressures $\sim$ 1 GPa) of prehnite-pumpellyite facies metamorphism, from which 2.7 Ga biological lipids have been successfully extracted (Brocks *et al.* 1999). Given the enormous informative value of biomarkers and the long-term stability of hydrocarbons (Mango 1991; Dutkiewicz *et al.* 1998), we believe it is not unreasonable to expect that new biomarkers, corresponding to the harsh conditions of lunar impact, could usefully be defined. Towards that end, we calculate the fraction of Terran material ejected from Earth at pressures ≤ 1 GPa and impacting the Moon at velocities $\leq 0.5\ km\ s^{-1}$.

B. Calculation of survival fractions

Until recently, the prospect that material could escape a planet via a natural process was considered extremely unlikely, much less that the material could do so without being heavily shocked (Melosh 1993). Experimental (Gratz *et al.* 1993) and observational evidence has forced a revision of this opinion. Most significantly, the SNC meteorites experienced shocks no greater than 45 GPa, with corresponding temperatures $\leq$ 600 C (Stoffler 2000, as cited by Mastrapa *et al.* 2001). In fact, ALH84001 apparently traveled from the surface of Mars to Earth without ever exceeding 40 C (Kirschvink *et al.* 1997; Valley *et al.* 1997; Weiss *et al.* 2000). Two mechanisms might account for these observations. During an oblique impact, a vapor plume jet could entrain and accelerate surface material to the escape velocity with little shocking (O'Keefe and Ahrens 1986). However, at low impact angle, most or all of this material will be derived from the impactor, while the viability of this method at higher impact angles (> 25 degrees) is uncertain (Pierazzo and Melosh 2000b). A second and more probable method, spallation, results in lightly shocked material due to the interference of the stress and rarefaction waves near a free surface. Our calculations are limited to this case.

The mass of spalled ejecta can be estimated using the method described in Melosh 1985,

$$M_e\left(>v_e\right)=\frac{0.75P_{max}}{\rho_t c_L v_i}\left[\left(\frac{v_i}{2v_e}\right)^{\frac{5}{3}}-1\right]m, \tag{38}$$

where M_e is the mass of the ejecta, v_e is the ejecta velocity, P_{max} is the maximum pressure experienced by this fraction of the ejecta, v_i is the velocity of the impactor, ρ_t is the target density (2860 $kg\ m^{-3}$ for basalt), c_L is the longitudinal speed of sound (6000 $m\ s^{-1}$) , and m is the mass of the impactor. This equation differs from that of Melosh 1985 only due to a mathematical error in the latter (for discussion and derivation of Equation 38, see Appendix 1).

Implicit to Eq. 38 is the assumption that the maximum ejecta velocity is one-half the impactor's. By making this conservative assumption, we preclude the escape of spalled ejecta for a most probable impactor velocity of 14 $km\ s^{-1}$; indeed, we require more rare impacts at velocities exceeding 22.4 $km\ s^{-1}$ for any spall escape. This suggests that most (but not all) Terran material on the Moon will be heavily shocked. Such material would nonetheless yield significant scientific returns, for example, by dating and characterizing the Late Heavy Bombardment on early Earth and in the young Solar System. Moreover, uncertainties pertaining to the velocity distribution of early Earth impactors and to maximal ejecta velocities have been treated conservatively in this paper. Faster impactors may have been more abundant 4 Ga than now (Sleep *et al.* 1989). Similarly, some laboratory experiments suggest ejecta velocities can actually approach 85% of the impactor velocity (Curran *et al.* 1977), which would enable escape for a 14 $km\ s^{-1}$ impactor.

Making these conservative assumptions we determine the percent of the total Terran material on the Moon that corresponds to the requirements set for each of the four classes of biological and geological evidence. Using Eq. 38, an ejecta velocity of 11.2 $km\ s^{-1}$, and the pressure and lunar impact velocity constraints imposed for the four material classes defined above, the mass of ejecta (in units of impactor mass) is derived over a range of impactor velocities (Table 5). We then divide this number by the fraction of ejected material escaping Earth determined from Eq. 4. Once deposited on the Moon, the material delivered at the end of the Heavy Bombardment is expected to be buried to a depth of roughly 6 meters within 5 million years, making protection from space radiation a second order effect. Our results, in terms of the percentage of Terran material on the Moon, are recorded in Table 6. For example, if all the material on the Moon were delivered by an impactor with velocity of $v_i = 22.5\ km\ s^{-1}$, over a10 x 10 square kilometer search area, the amounts of material having endured conditions permissive to the survival of molecular fossils, organics, volatiles, and isotopic signatures from early Earth are 0.4 kg, 9.2 kg, 28 kg, and nearly 80 kg, respectively.

[**Table 5, Table 6**]

V. CONCLUSIONS

In this paper, we have explored the Moon as an ideal location to search for remnants of the early solar system, particularly samples of Earth not currently available to researchers. The Moon's proximity and relatively unaltered surface makes research missions viable, and the Terran samples on the surface are unavailable anywhere else in the solar system. We have argued that Terran materials are abundant and near the surface, with a significant fraction retaining their geochemical and biological signatures for detailed analysis. In addition, since the majority of Terran samples date from the end of the Late Heavy Bombardment, the samples in the lunar "attic" are a unique probe of the early conditions on Earth, and potentially contain clues to the earliest forms of life.

The Terran material is delivered in one of two ways, through direct transfer or orbital transfer. We have found that orbital transfer of material is more efficient for the time since the end of the Late Heavy Bombardment, with direct transfer of material only comparable in early epochs. The amount of Terran material, 7 ppm, is sufficiently large to consider a search mission.

Before any such mission is attempted, the current stock of lunar material (approximately 400 kg worth) should be searched for Terran material. Given a concentration of 7 ppm, there should be roughly 3 grams of Earth material in the current lunar samples. Since lunar fines contain more than 10 million particles per gram, a technique of infrared spectroscopy coupled with microscopic imagery could distinguish hydrated silicates (common on Earth) from the dry, unhydrated lunar fines. Such material could then be isotopically analyzed to confirm its terrestrial origin. While this is not likely to yield much in the way of information about the early Earth, it would act as a proof of concept and a baseline for future missions.

Recovery and identification of Terran samples from the Moon represents a significant challenge. Still, returning a sample from the Moon bearing the remains of Earth life may be orders of magnitude easier than returning, say, Martian samples from Mars bearing the remains of Martian life. In this sense, lunar missions represent an interesting proving ground for these types of endeavors. The risk of contamination and relative scarcity of Terran material makes sample return missions difficult. Therefore, robotic missions need to be developed capable of finding Terran material using advanced in situ measuring devices to help identify samples and largely driving the analysis on the Moon. The existence of a facility on the Moon to recover and analyze samples would guard against any contamination from Earth. However, for a complete analysis of the material, we suggest the best way to conduct these studies is on site measurements by human observers - in essence, a return to the Moon.

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Appendix A. Justification of Eq. 38

The expression for the mass of spalled ejecta as a function of ejection velocity is based on that described and physically justified by Melosh 1985. Briefly, Melosh derived an equation for the spall thickness, z_s:

$$z_s = \frac{TD}{\rho_t C_L v_e}, \tag{39}$$

where T is the dynamic tensile strength and D is the impactor diameter. Integration of this equation gives the volume of spalled ejecta.

An expression for v_e can be deduced from the supplementary material to Melosh 1985, still available from GSA,

$$v_e = 2v_i \left(\frac{D}{2R}\right)^3, \tag{40}$$

where R is the radial distance from the impact epicenter to the point of ejection.

Thus, z_s is inversely proportional to v_e and directly proportional to the cube of R. If a sign error is made, such that z is mistakenly assumed proportional to R^{-3}, one derives the equation given in Melosh 1985.

Avoiding that error, the volume of spalled ejecta can be determined by evaluating the integral

$$\int_{R_{min}}^{R_{max}} 2\pi R z_s\left(R\right) dR, \tag{41}$$

where the limits of integration are defined by the maximum and minimum ejecta velocities being considered, corresponding to $R_{min} = \left(\frac{D}{2}\right)(4)^{\frac{1}{3}}$ and $R_{max} = \left(\frac{D}{2}\right)\left(\frac{2v_i}{v_e}\right)^{\frac{1}{3}}$. The maximum ejecta velocity, corresponding to R_{min}, has been assumed equal to half the impactor's velocity, as in Melosh 1985.

Evaluating this integral and substituting $T = \frac{P_{max}}{\beta}$ (see footnote 4 in Melosh 1985), with $\beta \sim 4$, gives the equation used in this paper.

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Table 1. The fraction of impactor mass delivered to the Moon for a range of Earth-Moon distances. η is the Earth-Moon distance in Earth radii and v_{min} is the velocity of the shell's trailing edge. The orbital period of the Moon and its interaction time with the shell are given, in days. F_{direct} is the fraction of the impactor mass that reaches the Moon.

η	$v_{min},\ km\ s^{-1}$	Orbital Period, days	Interaction Time, days	F_{direct}
21.6	10.94	5.9	0.30	2.0×10^{-6}
26.5	10.99	8.0	0.40	1.2×10^{-6}
31.3	11.02	10.2	0.50	7.9×10^{-7}
36.2	11.05	12.7	0.58	5.3×10^{-7}
41.0	11.06	15.3	0.66	3.9×10^{-7}
45.9	11.08	18.1	0.78	2.9×10^{-7}
50.7	11.09	21.1	0.84	2.2×10^{-7}
55.5	11.10	24.1	0.91	1.7×10^{-7}
60.3	11.11	27.3	0.99	1.4×10^{-7}

Table 2. Impact results for orbital transfer. $\frac{N_\oplus}{N_m}$ is the ratio of Terran to lunar impacts, from Eq. 8, $f_\oplus$ is the fraction of particles returning to the Earth, and f_m is the fraction of particles returning to the Moon. Also listed are the expected number of lunar impacts from the scaling arguments, the lunar transfer efficiency, F_e, and the fraction of the impactor mass transferred to the Moon via this method, F_{orb}.

v_∞ $km\ s^{-1}$	Earth impacts	Lunar impacts	$\frac{N_\oplus}{N_m}$	$f_\oplus$	f_m	Scaled lunar impacts	F_e	F_{orb}
0.0	138	1	140.0	0.61	0.004	0.98	4×10^{-3}	3×10^{-7}
1.0	14	0	130.4	0.06	0.0	0.11	5×10^{-4}	5×10^{-7}
1.8	5	1	113.3	0.02	0.004	0.04	2×10^{-4}	2×10^{-7}
2.3	1	0	101.5	0.004	0.0	0.01	4×10^{-5}	2×10^{-8}
2.7	1	0	92.4	0.004	0.0	0.01	4×10^{-5}	4×10^{-6}
3.3	1	0	80.0	0.004	0.0	0.01	4×10^{-5}	5×10^{-6}

Table 3. Lunar impact velocities. Listed are the most likely impact velocities for an angle less than or equal to θ, the probability that a given impact is less than or equal to θ, and the corresponding impact pressures experienced by the impactor on the Moon.

v_{exp} $km\ s^{-1}$	θ, degrees	$P\,(\leq \theta)$	Impact Pressure, GPa
5.0	90	1.00	48
2.5	77	0.95	12
2.0	64	0.81	8
1.0	45	0.50	2
0.5	35	0.33	0.5
0.1	20	0.12	0.02

Table 4. Values of the fit parameters for the lunar cratering record.

α	β	γ	τ, Gyrs	μ, Gyrs	τ_c, Gyrs	χ^2
2.24×10^{-5}	9.82×10^{-11}	-	0.144	-	-	0.50
2.26×10^{-5}	3.57×10^{-12}	1.27×10^{-3}	0.129	3.9	0.07	0.99

Table 5. Ejected material as fractions of the impactor mass calculated for the different velocity and ejecta pressure regimes. v_i is the impactor velocity, M_e is the ejecta mass, and M_i is the impactor mass.

v_i $(km\ s^{-1})$	M_e/M_i 1 GPa	M_e/M_i 10 GPa	M_e/M_i 30 GPa	M_e/M_i 70 GPa
14	no escape	no escape	no escape	no escape
22.5	1.45×10^{-5}	1.45×10^{-4}	4.34×10^{-4}	1.01×10^{-3}
25	3.51×10^{-4}	3.51×10^{-3}	1.05×10^{-2}	2.46×10^{-2}
30	9.14×10^{-4}	9.14×10^{-3}	2.74×10^{-2}	6.40×10^{-2}
40	1.78×10^{-3}	1.78×10^{-2}	5.34×10^{-2}	1.25×10^{-1}
50	2.46×10^{-3}	2.46×10^{-2}	7.38×10^{-2}	1.72×10^{-1}
65	3.30×10^{-3}	3.30×10^{-2}	9.89×10^{-2}	2.31×10^{-1}

Table 6. Of the Terran material on the Moon, the mass fraction from a given impact that arrived there under conditions conducive to the survival of molecular fossils, organics, significant volatile inventories, or isotopes. The fractions of material with lunar impact velocities of $\leq 5\ km\ s^{-1}$, $\leq 2\ km\ s^{-1}$, and $\leq 0.5\ km\ s^{-1}$ are 1.0, 0.81, and 0.33 respectively (see Table 3).

v_i $km\ s^{-1}$	Biomarkers %	Organics %	Volatiles %	Isotopes %
14	no escape	no escape	no escape	no escape
22.5	0.002	0.05	0.14	0.40
25	0.04	0.99	2.96	8.53
30	0.09	2.06	6.19	17.8
40	0.12	2.84	8.53	24.6
50	0.12	3.01	9.02	26.0
65	0.12	2.94	8.83	25.4

FIGURE CAPTIONS:

Figure 1. The cumulative number of impacts as a function of time for the simulation with $v_\infty = 0.0\ km\ s^{-1}$. Most of the impacts (123 out of 138) occur within the first 100 years, and the rate tapers off substantially after 1000 years.

Figure 2. Analytical fits to the BVSP dataset for two models of the time evolution of impactor flux. The dashed line is the lunar cataclysm, and the solid line is the exponential model. The plot is the cumulative crater density per square kilometer (in both size and time) for craters larger than 4 km shown with the BVSP data. The effects of the lunar cataclysm can be seen around 3.9 Ga.

Figure 3. Plot of the total regolith depth accreted as a function of time. The lines correspond to the models as stated in Fig. 2

Figure 4. Plot of the fractional volume of Terran material as a function of time in the lunar regolith. The lines correspond to the models as stated in Fig. 2